Fuel Ethanol Production Using Nuclear-Plant Steam

Charles W. Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008; Oak Ridge, TN 37831-6165
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

Samuel Rosenbloom
U.S. Department of Energy, Washington, D.C.
Tel: (301) 903-5749; E-mail: samuel.rosenbloom@eh.doe.gov

Richard Black
U.S. Department of Energy, Washington D.C.
Tel: (301) 903-0104; E-mail: richard.black@hq.doe.gov

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ABSTRACT

In the United States, the production of fuel ethanol from corn for cars and light trucks has increased from about 1.6 billion gallons per year in 2000 to 5 billion gallons per year in 2006. It is projected by 2030 that up to 30% of the liquid fuels consumed in the United States could be made from biomass [1, 2] with an ultimate production capability twice as large. Long-term studies [3] indicate that biofuels could provide about 30% of the global demand in an environmentally acceptable way without impacting food production. Rapid expansion of liquid fuels production from biomass is predicted for many other parts of the world as well. Sugarcane and corn are the primary feedstocks today, but future plants are expected to also use abundant cellulose. The rapid growth in biomass-to-ethanol plants is a result of three factors: new biotechnologies that are dramatically improving the economics; increased concern about global warming, which generates renewed interest in renewable liquid fuels; and the high cost of oil.

The production of fuel ethanol from biomass requires large quantities of steam. For a large ethanol plant producing 100 million gallons of fuel ethanol from corn per year, about 80 MW(t) of 150-psi (~180ºC) steam is required. Within several decades, the steam demand for ethanol plants in the United States is projected to be tens of gigawatts, with the worldwide demand being several times larger.

There are strong incentives to use steam from nuclear power plants to meet this requirement. The cost of low-pressure steam from nuclear power plants is less than that of natural gas, which is now used to make steam in corn-to-ethanol plants. The use of steam from nuclear power plants reduces greenhouse gases compared with the generation of steam from fossil fuels. Last, in cellulose-to-ethanol plants the liquid fuel produced per unit of biomass can be substantially increased if the plants also have the capability to convert lignin to liquid fuels. Lignin is the primary non-sugar-based component in cellulosic biomass that can not be converted to ethanol. It is planned to use this lignin as boiler fuel in these ethanol plants; however, if there are other sources of steam it may be feasible to also convert the lignin to liquid fuels and thus increase the yield of liquid fuels per unit of cellulosic biomass. In several decades, this market may become in several decades the largest market for cogeneration of steam from nuclear electric power plants.

1. INTRODUCTION

Within the last 5 years, new technologies and new requirements have resulted in dramatic increases in liquid fuels production from biomass. These changes open up a new large market for nuclear cogeneration of steam for (1) electricity and (2) process plants that convert biomass to liquid fuels. The technologies and changes are described herein.

2. ETHANOL: THE FUEL

As a liquid fuel, ethanol has long-term advantages. If produced from biomass, it can be a renewable greenhouse-free liquid fuel. Green plants use solar energy and carbon dioxide from the atmosphere to produce the biomass, which is then converted to ethanol. The burning of the ethanol returns the carbon dioxide to the atmosphere. The environmental hazards of ethanol are less than those of gasoline or other traditional fuels because ethanol is quickly degraded to carbon dioxide and water in the environment by various bacteria.

Ethanol is increasingly being used as a transport fuel in three different ways. First, ethanol has an octane rating of 113–115 and therefore is used as an octane enhancer. It is replacing MTBE, a hydroscopic octane enhancer that has caused significant groundwater contamination and has major legal liabilities associated with its use. Second, ethanol is used to meet the minimum oxygen-content requirements for gasoline. Some oxygen is required in gasoline to minimize carbon monoxide pollution from vehicles and pollutants that produce ozone. Last, ethanol is a fuel, both when mixed with gasoline and when used alone. However, the values of ethanol as an octane enhancer and as a means of achieving minimum oxygen requirements for the fuel are significantly higher than its fuel value. If ethanol became widely available, engine performance and efficiency could be improved by taking advantage of the very high octane rating it offers.

3. THE REVOLUTION IN FUEL ETHANOL PRODUCTION

The potential benefits of fuel ethanol have long been understood; however, it is the development of new biotechnologies that are beginning to make this option a technically and economically viable option in large parts of the world. There are four biomass feedstocks, each which requires a somewhat different technology.

Monomeric sugars. Traditional fermentation can directly convert simple sugars such as those from sugar cane and sugar beets into alcohol. This is the primary method that has been used to produce alcohol for human consumption for thousands of years. However, the availability of these feedstocks is limited because they are also used for food. Today most of the fuel ethanol from simple sugars is made from sugarcane in Brazil, where the combination of land, labor, and climate provides favorable economic conditions.

Starch. Starch is a biopolymer of glucose, a monomeric sugar. It is the primary component of corn and other grains. Starch cannot be directly fermented to alcohol. An enzyme is required to break it down into simple sugars. The simple sugars can then be fermented to alcohol. While brewers learned long ago how to use natural enzymes to achieve this conversion, only in the last several decades has modern industrial enzyme technology developed methods to make inexpensive enzymes to allow economic production of fuel ethanol. Those technical developments have made possible the new fuel ethanol industry in the United States based on corn. The availability of starch is an order of magnitude larger than that of monomeric sugars but is also constrained because starch is a food for humans and many farm animals.

Cellulose. Cellulose is the most common form of biomass and is also a biopolymer of glucose. It is structured to be difficult to break down and thus serves as a defense mechanism for plants, because only some animals can digest cellulose.

Hemicellulose. Hemicellulose is the fourth sugar biopolymer. However, unlike the other sugars, it is a highly branched chain of five- and six-carbon sugars. It is the second most common form of biomass. Like cellulose, only some animals have the capability to digest it.

Cellulose-rich feedstocks contain 40–60% cellulose, 20–40% hemicellulose, and 10–25% lignin. Lignin is a nonsugar biopolymer which will be discussed later. Like starch, cellulose and hemicellulose can be broken down into their sugars with appropriate enzymes. However, much more sophisticated enzymes are required to break down these biopolymers [4]. In the last decade, the development of low-cost enzymes to break down these biopolymers to monomeric sugars now makes it appear possible to economically convert these feedstocks to ethanol. The first pilot plants are now in operation, and industrial facilities are expected to follow. The available cellulosic biomass is an order of magnitude larger than the available supplies of starch and is sufficient to meet a significant fraction of the world's liquid fuel demands. New technologies are expected to significantly increase cellulose yields as an energy crop [5]. The large projected growth in fuel ethanol production is based on the commercialization of this technology.

4. BENEFITS OF USING NUCLEAR ENERGY TO SUPPLY STEAM

Biomass is not a free energy source. Large quantities of energy are required to grow biomass and convert it into ethanol. The non-solar-energy input to grow the biomass (e.g. corn) and convert it to ethanol is typically about 70 to 80% of the energy value of the ethanol [6]. About half of this energy is in the form of low-temperature, low-pressure (150-psi) steam [7]. The fermentation of sugars yields a mixture of water and alcohol, with alcohol contents of ~15%. Distillation, an energy-intensive process, is required to separate the ethanol from the water. Smaller quantities of steam are required to sterilize the feed before fermentation and drying of various secondary products. A typical flowsheet for the conversion of corn to ethanol and animal food is shown in Fig. 1. Today different sources of energy are used to provide the steam.

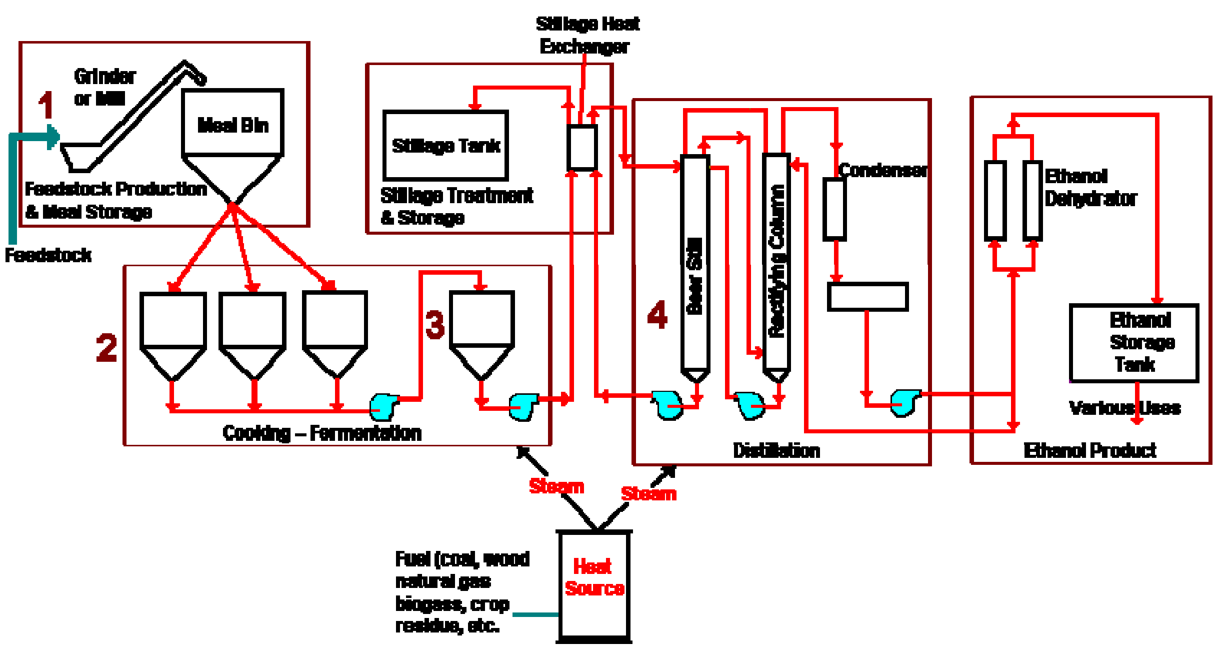

FIG. 1. Flowsheet for conversion of corn to fuel ethanol and animal food.

Monomeric sugars. In Brazil sugarcane in Brazil is the primary feedstock to produce ethanol from simple sugars. The sugar cane is squeezed to separate the sugar water from the cellulose-rich cane called bagasse. The bagasse is burned to provide the energy for the ethanol plant.

Starch. In the United States corn is the primary starch that is converted to ethanol. Corn contains starch in the form of carbohydrates and proteins. In the corn-to-ethanol process, the fermentation step converts the carbohydrates to ethanol, which uses about two-thirds of the corn kernel. The nonfermentable components, which consist primarily of proteins and the other by-products of fermentation, become animal food or are converted to other useful products. Because of the value of the protein as an animal food, these by-products are not burnt to produce energy to operate the plant. In most cases, natural gas is used to provide the energy to operate the plant.

Cellulose and hemicellulose. The current plans to convert these materials to ethanol assume that the lignin associated with the cellulose and hemicellulose will be burnt to provide energy.

Nuclear power plants excel in the production of steam. That capability enables them to cogenerate electricity and steam, with the steam used to operate ethanol plants. For ethanol production, steam would be provided by the reactor. In the ethanol plant, the steam would be condensed, and warm water would be returned to the nuclear power plant. Almost all of the heat would come from condensing the steam. Modern steam systems would allow more than a mile of separation between the reactor and the ethanol plant. Ethanol plants would have to be located beyond any security perimeter because such plants require easy access by grain trucks, trains, or barges. The separation required to avoid security concerns would be more than necessary to ensure safety against fires and other accidents in the ethanol plant.

There are multiple incentives to use steam from nuclear power plants, as outlined in the following subsections.

4.1 Economics

After the cost of biomass, energy is the second largest cost in the production of fuel ethanol. For the production of ethanol from corn (starch) in the United States, the energy to make the steam is provided by natural gas. Steam from existing nuclear power plants in the Corn Belt and along the Mississippi River can potentially be supplied at significantly lower costs than steam from fossil fuels.

The price of nuclear plant steam can be estimated from the price of electricity. A nuclear power plant produces steam that can be sold or used to produce electricity. The utility will demand at least the same revenue from the sale of steam as from the sale of electricity. A rough estimate of the price of steam can be calculated from the wholesale price of electricity, as clarified in the following example. The price of electricity varies across the country; thus, this example will use the recent average market price for wholesale electricity in Minnesota which is \$53.89/MWh(e). Minnesota is a major producer of fuel ethanol in the United States and has nuclear reactors at Monticello and Prairie Island. The efficiency of nuclear power plants is ~33%; that is, if one less Btu of electricity is produced, 3 Btus of steam become available. However, nuclear reactors produce high-temperature steam whereas ethanol plants require only relatively low-temperature steam. In converting high-temperature steam to electricity, 40% of the electricity is obtained by the time the steam pressure is 150 psi (suitable for ethanol production), with the remaining 60% of the electricity produced in the low pressure turbines. Using this information, a rough estimate can be made of the corresponding price of steam from a nuclear plant given the price of electricity:

$$\$53.89/\text{MWh(electricity)} \cdot 0.33 \cdot 0.6 = \$10.67/\text{MWh(steam)} = \$3.13 \text{ per million Btu.}$$

This cost represents less than half the price of natural gas in the United States. Similar economics apply to the cogeneration of low-temperature steam almost everywhere in the world. There is also the potential for additional savings. The price of electricity is lower at night than during the day. If some of the steam demand (such as for by-product drying) can be shifted to the nighttime, steam costs may be one-half or one-third as much.

4.2 Greenhouse Impacts

Using steam from nuclear plants would reduce in half the greenhouse gas releases in the production of ethanol by reducing fossil fuel usage.

4.3 Full Use of Biomass

Recent U.S. studies [1] indicate that biomass (primarily cellulose) could provide 30% of the liquid fuel demand by 2030. The primary limitation is the availability of biomass. If steam from nuclear plants can displace bagasse (primary cellulose) from sugarcane-to-ethanol plants or lignin from cellulose-to-ethanol plants as the energy source, these sources of biomass could be used to produce more liquid fuels. In effect, nuclear energy directly increases the production of liquid fuels per unit of biomass that is harvested.

5. LIMITATIONS

5.1 Biomass Transportation

Biomass is bulky, heavy, and expensive to transport. As a consequence, ethanol plants are located where biomass is available or where the by-products can be sold. This limits the potential sale of steam from nuclear plants to those plants near large sources of biomass or to river locations where low-cost barge transport may allow long-distance transport of biomass. In the United States today, most of the nuclear plants that can economically provide steam for this application are in the Corn Belt or along the Mississippi River or other waterways where cheap barge transport is available (Fig. 2).

The size of ethanol plants has grown rapidly. New large ethanol plants require ~100 MW(t) of steam. Plant size is increasing but will ultimately be limited by biomass transport costs. Except for river sites, this will likely limit the market for steam from most nuclear sites to a few hundred megawatts. These logistic constraints imply a major market for cogeneration of steam from nuclear reactors for ethanol production. However, construction of large nuclear reactors dedicated to ethanol production is less likely. Instead, nuclear power represents a market for cogeneration of electricity and steam.

5.2 Institutional

The idea of using nuclear power plants to coproduce electricity and heat is not new. Since the beginning of the development of nuclear energy [8], steam has been used for district heating (45 reactors), desalting (10 reactors), and industrial purposes (25 reactors). Canadian nuclear power plants have been used to produce electricity and steam, with the steam used for the isotopic separation of heavy water and other industrial purposes. This included the use of steam from the Bruce Nuclear Power Station in Canada for about a decade for the production of ethanol. Plants in Switzerland and Russia produce both electricity and district heat. In the United States, a two-unit nuclear plant was partially built at Midland, Michigan, to produce electricity and steam for the Dow Chemical Company. However, applications have been limited. One reason is that the prices of fossil fuels have been low. Equally important, very few markets exist for large quantities of steam. It is not usually worth the effort to modify a nuclear power plant producing 1500 to 4500 MW of steam to produce a few megawatts of heat to meet a local-industry or district-heating need.

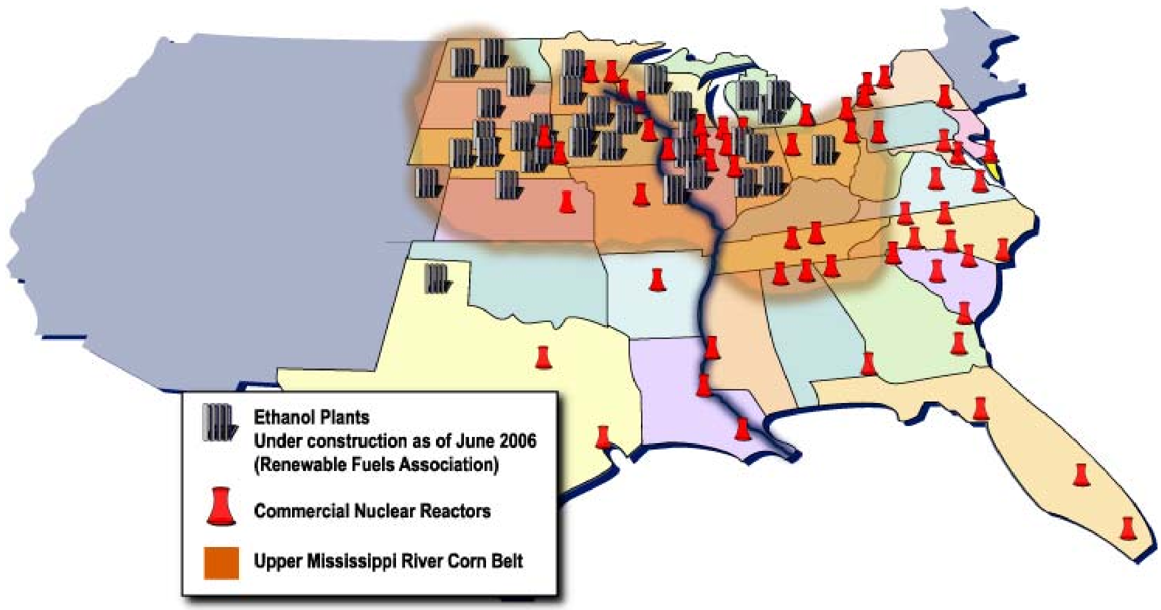

FIG. 2. Ethanol plants under construction, existing nuclear power plants, and the corn belt.

The development of fuel-ethanol production from corn in the last 5 years is now creating a new potential market for large quantities of steam from nuclear power reactors. The size of corn-ethanol plants is rapidly increasing, as is the corresponding steam demand per plant. The plants that produce ethanol from corn operate continuously, resulting in a steady-state demand for steam. In the production of ethanol, the primary cost is corn, followed by the cost of energy—thus, the economic incentive to consider steam from nuclear power plants. Finally, the demand for steam is located in rural areas where nuclear power plants already exist. This represents a new market that did not previously exist. Only with the development of large corn-to-ethanol plants and the coming development of cellulose-to-ethanol plants does a market now exist. The new market, with its own specific constraints, will require the development of appropriate business structures to combine nuclear steam with ethanol production.

5.3 Cellulose-to-Ethanol

The new corn-to-ethanol market in the United States may enable up to 30 existing reactors to sell steam for ethanol production. However, this is a small market limited to a few countries compared with the future global cellulose-to-ethanol market. To enter the latter market, chemical processes must be developed to convert lignin into liquid fuels [4, 9] or other uses [10]. Lignin is a complex biopolymer made by plants from various phenylalanines that is not consumed in a cellulose-to-ethanol plant. For this type of plant, plans are to burn the lignin to produce steam. With high fossil-fuel prices, lignin is the low-cost energy source for such plants—unless nuclear steam is available.

There are multiple ways to convert lignin to liquid fuels [4, 9]. The Fisher-Tropsch process, which is used to convert other carbon-based materials to liquid fuels, can be used. However, this process is typically used on a much larger scale of operations. Lignin provides a low-sulfur, highly uniform feed that should improve the economics of smaller-scale plants. However, this potential has not been fully examined. Research is also under way to convert this biopolymer to high-octane (>100 octane number) gasoline additives and other useful compounds by various catalysts. The need is to accelerate this work—something that will happen with the recognition that steam from nuclear power plants could provide a low-cost alternative energy source to operate ethanol plants and free lignin for other uses.

6. CONCLUSIONS

Markets ultimately determine the demand for steam from nuclear power plants. An ongoing revolution in biotechnology is driving down the cost of biomass-to-ethanol. Biomass-to-ethanol plants require very large quantities of low-temperature steam. The growth of the ethanol market may soon create a major market for cogeneration of steam from nuclear power plants. The ultimate size of this market is measured in hundreds of gigawatts of thermal energy and thus may become the dominant cogeneration market for nuclear heat. The corn-to-ethanol plants provide the near-term market for nuclear steam. The much larger market, the future cellulose-to-ethanol plants, is a longer-term market for nuclear steam that required development of lignin-to-fuels or other lignin-to-other-products.

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